IAC-05-A5.2.03

RPS STRATEGIES TO ENABLE NASA'S NEXT DECADE ROBOTIC MARS MISSIONS

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ABSTRACT

NASA's proposed roadmap for robotic Mars exploration over the next decade is influenced by science goals, technology needs and budgetary considerations. These requirements could introduce potential changes to the succession of missions, resulting in both technology feed forward and heritage. For long duration robotic surface missions at locations, where solar power generation is not feasible or limited, Radioisotope Power Systems (RPS) could be considered. Thus, RPSs could provide enabling power technologies for some of these missions, covering a power range from 10s of milliwatts to potentially a kilowatt or even higher. Currently NASA and DoE with their industry partners are developing two RPSs, both generating about 110 We at BOL. These systems will be made available as early as 2009. The Multi-Mission Radioisotope Thermoelectric Generator (MMRTG) – with static power conversion – was down-selected as a potential power source for the MSL mission. Development of small-RPSs is in a planning stage by NASA and DoE; potentially targeting both the 10s of milliwatts and 10s of watts power ranges. If developed, Radioisotope Heat Unit (RHU) based systems – generating 10s to 100s of milliwatts – could power small adjunct elements on larger missions, while the GPHS module based systems – each generating 10s of watts – could be stacked to provide the required power levels on MER class surface assets. MMRTGs and Stirling Radioisotope Generators (SRGs) could power MSL class or larger missions. Advanced Radioisotope Power Systems (ARPS) with higher specific powers and increased power conversion efficiencies could enhance or even enable missions towards the second half of the next decade. This study examines the available power system options and power selection strategies in line with the proposed mission lineup, and identifies the benefits and utility of the various options for each of the next decade launch opportunities.

INTRODUCTION

The Mars exploration pathway is one of the three major pathways identified in the Vision for Space Exploration [1]. To implement this plan, NASA's Advanced Planning and Integration Office (APIO) established two sets of teams over the past year; one focusing on strategic and another on capability goals. The teams addressed activities performed within the Science Mission Directorate (SMD) and Exploration Systems Mission Directorate (ESMD). These studies were completed by May 2005. Subsequently, NASA's Administrator initiated a 60-day study to further refine future plans related to ESMD. Findings of these assessments are gradually emerging, but at the time of writing this paper only general directions are available for discussion purposes. The Mars Exploration Program is governed by four goals, established by the Mars Exploration Program Analysis Group (MEPAG) [2]. These goals are:

1. Determining if life ever arose on Mars;

2. Understanding the process and history of climate on Mars;

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3. Determining the evolution of the surface and interior of Mars; and

4. Preparing for human exploration.

The first three goals are science driven while the fourth is primarily technology focused. All of these can be translated into a number of robotic and human precursor missions, leading to a possible human landed mission by around 2035. While the order of these missions could change from the one reported in [3], it is anticipated that similar mission types will be required to address the four MEPAG defined goals, programmatics and budgetary considerations.

Therefore, this paper discusses potential next decade Mars exploration missions and the connected enabling power system options and strategies, with a special focus on Radioisotope Power Systems (RPS).

POWER SYSTEM OPTIONS

While the present paper focuses on RPS options and usage, a brief summary of other power options are also provided. Space power technologies can be grouped into external and internal power source categories. The first group include solar power and power beaming, while the second covers radioisotopes and fission power. With the internal power sources heat is generated internally then it is converted into electricity using various – static or dynamic – conversion technologies. A summary of these power source options is shown in Figure 1.

RPS Options

The first New Frontiers mission – the New Horizons Pluto-Kuiper Belt mission, with a planned launch date in January 2006 – would utilize a single General Purpose Heat Source Radioisotope Thermoelectric Generator (GPHS-RTG). This type of RPS has been also flown on the Galilo, Cassini-Huygens and Ulysses missions. With 18 GPHS modules a GPHS-RTG generates 4500 W(t) of thermal power, which is then converted to ~285 W(e) electric power at the beginning of life (BOL). It utilizes thermoelectric conversion, with SiGe thermocouples. Performance characteristics of a GPHS-RTG are shown in Table 1. Although the specific power (~5.2 W/kg) seems higher than those for other RPSs under development, there are many difference between the designs to account for them. GPHS-RTGs were designed for in-space operation only, making the thermal insulation lighter. It was also designed for the launch environments of Delta-II or Titan launch vehicles. Launching them on a more demanding Delta-IV Heavy launch vehicle would require the addition of heavy acoustic tiles. The GPHS modules were also improved for the next generation of RPSs, resulting in slightly higher dimensions. It was calculated that once these differences are addressed, the specific power for GPHS-RTGs would reduce to a level comparable to the new RPSs discussed below. Following the New Horizons mission, NASA/DoE could assemble one more GPHS-RTG unit from currently existing parts, but restarting GPHS-RTG manufacturing was found to be not cost effective. Consequently, GPHS-RTGs are planned to be phased out after this mission.

NASA and DoE – with their industry partners – are currently developing two types of RPSs. They are called Multi-Mission Radioisotope Thermoelectric Generator (MMRTG) using static power conversion, and Stirling Radioisotope Generator (SRG), employing dynamic power conversion. Both systems are required to generate at least 110 W(e) at BOL. Concepts of these two systems are shown in Figure 2, while a projected performances are summarized in Table 1.

An MMRTG uses 8 General Purpose Heat Source (GPHS) modules. The design capitalizes on 30 years of flight heritage from previous missions, including Voyager (MHW-RTG; ~150 W(e)); Viking 1 & 2, Pioneer 11 (SNAP-19; ~40 W(e)); Galileo, Cassini-Huygens, and Ulysses (GPHS-RTG; ~285 W(e)); and Apollo 12/ 14/ 15/ 16/ 17 (Apollo Lunar Surface Experiment Package-ALSEP; ~70 W(e)). The specific power of an MMRTG is ~2.9 W/kg, with a corresponding current best estimate mass of ~44 kg. It generates ~125 W(e) at BOL. This new design is multi-mission capable, that is, an MMRTG can operate both in atmospheres and in vacuum, while the GPHS-RTG is limited to
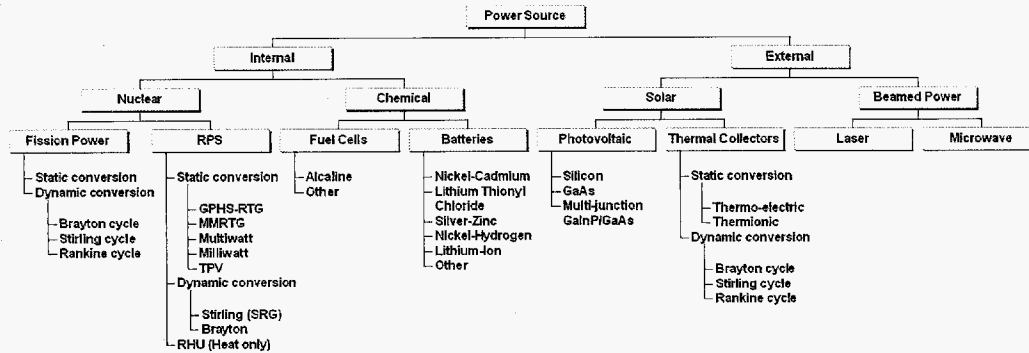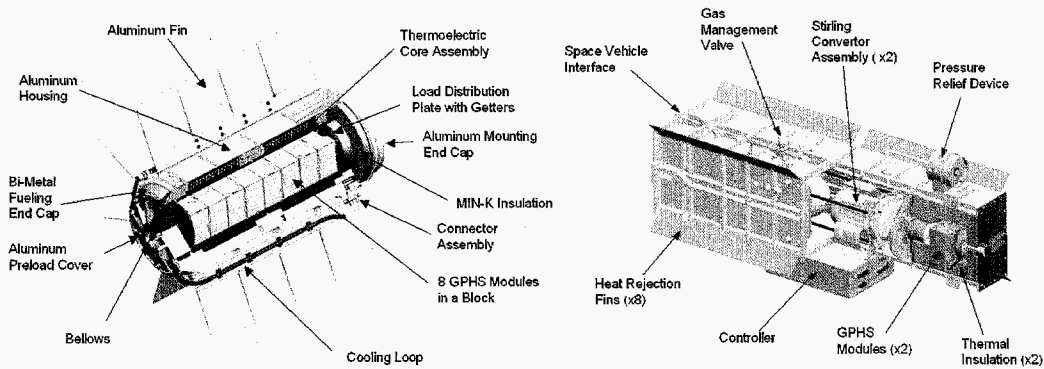
Figure 1: Categorization of Power Sources

Figure 2: RPS Concepts Under Development, MMRTG (left) and SRG (right)

Parameter	MMRTG	Upgraded MMRTG	SRG	GPHS-RTG
Power per Unit (BOM), W(e)	~125	~160	~116	~285
Mass per Unit, kg	~44	~40	~34	56
# of GPHS Modules per Unit	8	8	2	18
Thermal Power, W(t)	2000	2000	500	4500
Specific Power, W(e)/kg	2.9	4.0	3.4	5.2
Conversion type	Static	Static	Dynamic	Static
Converter materials	PbTe/TAGS	Scutterudites	Stirling	SiGe
Technical Readiness level	TRL-5	TRL-3	TRL-3	TRL-9
Availability	MSL-2009	2014+	2012+	Discontinued

Table 1: Performance summary predictions for 4 RPS designs. Two of them are currently under development by NASA/DoE with industry partners (MMRTG & SRG); one is suggested for future missions (upgraded MMRT); and one will be discontinued after the launch of the first New Frontiers mission in 2006. The upgraded MMRTG was conceived as a modified standard MMRTG, where the existing PbTe/TAGS thermoelectrics would be replaced with higher efficiency scutterudite thermoelectrics.

in-space operation only. It is radiation tolerant to the multi-MRad level – making it suitable for future planned missions to the Jovian system – and it can tolerate g-loads up to 40g, which corresponds to the launch environment on a Delta IV-H launch vehicle. Static power conversion does not generate EMI radiation that could interfere with science measurements. Almost 2 kW(t) of remaining excess heat – following the power conversion – could be utilized, in order to keep spacecraft components within a required temperature range. In contrast to these advantages, thermoelectrics have low power conversion efficiencies ($\sim$6.2%) The overall power system degradation is estimated at $\sim$1.6%, half of it is due to natural radioisotopic decay and the other half is to the degradation of the thermoelectrics. At the same power output it uses about 4 times more Plutonium-238 (Pu^{238}) fuel, and it is also heavier than the Stirling Radioisotope Generator.

Upgraded MMRTG designs are under consideration with higher power conversion efficiencies (from today's $\sim$5.5-6.5% to $\sim$8-10% within 10 years), addressed through improved or new thermoelectrics. These advanced MMRTGs would target specific powers of 5 W/kg and above. (Note that specific power levels of 8 W/kg and above are required to make Radioisotope Electric Propulsion (REP) feasible.) Upgraded systems could be made available for future missions as early as the middle of the next decade.

The second RPS under development is the Stirling Radioisotope Generator (SRG). It uses 2 GPHS modules generating 500 W(t). Two dynamic Stirling generators convert some of this heat into $\sim$116 W(e) at BOL. The power system degradation is assumed at $\sim$0.8% per year, due to radioisotopic decay. Degradation of the dynamic power conversion system was no assessed and was considered negligible.

SRGs offer a few distinct advantages over static converter based systems. SRGs have significantly higher conversion efficiencies, in the range of today's $\sim$22% to the next generation of $\sim$32%. For the present system the conversion efficiency is about 4 times higher than that of the thermoelectric conversion. Consequently, for the same power output SRGs require about 75% less Pu^{238} fuel, which can be an important consideration

if the plutonium supply becomes limited. This lower fuel requirement (1 kg vs. 4 kg for the MMRTG) could also significantly reduce the fuel cost per power unit, by as much as $\sim$\$6M based on an assumed fuel cost of \$2000 per gram of Pu^{238} [4]. Because of its lower mass ($\sim$34 kg), the specific power of an SRG-110 unit is about 3.4 W/kg, compared to 2.9 W/kg for the MMRTG. The SRG design is also multi-mission capable. In short, SRGs are more efficient; require less plutonium; and lighter. The lower Pu^{238} requirement also results in 75% less heat generation, which may simplify cruise-phase thermal designs for missions where a lander is encapsulated in an aeroshell until the completion of EDL. Beside these advantages, SRGs also have both real and perceived limitations. Stirling Radioisotope Generators are not yet space qualified. Lifetime for these dynamic converters is not yet proven (especially when considering outer planets missions lasting for up to 10-20 years). The SRG g-load tolerance requirement is currently 30g, somewhat lower than that for an MMRTG. This is suitable to tolerate the launch environment, but limits landing to soft landing configurations only. Controller electronics are rather sensitive to high radiation environments – such as at Jupiter – and controller radiation shielding could significantly increase the total unit mass. In case of failing one of the two Stirling converters, the whole unit could become unbalanced, resulting in the failure of the other converter half. Furthermore, EMI radiation could interfere with sensitive science measurements. EMI shielding could somewhat mitigate this effect, but that again would add mass to the system and would add complexity to the design. Finally, it is required to provide redundancy for these dynamic power systems. This means that each SRG enabled mission must carry a redundant unit, which lessens the power system mass gains against other RPS configurations. The next step in SRG development includes the completion of an engineering unit by 2010 or 2012. Although the SRG-110 power system was not selected for MSL, the Stirling community is hopeful that future Moon missions may provide a proofing ground for this technology.

Future RPSs were considered up to $\sim$5 kW(e). Such configurations are based on the assump-

tion that the system would use about the same amount of Pu^{238} as used on the Cassini-Huygens missions (i.e., ~27 kg). In addition, the system would utilize dynamic power conversion, with a conversion efficiency about 5 times higher than that of the static converter used on the GPHS-RTG. This configuration is highly conceptual and needs a significant development effort.

Finally, RPS developments could also include small-RPSs [5] [6], generating power in the ranges of 10s to 100s of milliwatts or 10s of watts. The former would use multiple Radioisotope Heater Units (RHU: 1 W(t) each), while the latter would employ a GPHS module. Both configurations would utilize thermoelectric (or potentially dynamic) power conversion. Mission concept examples for Mars exploration, enabled by small-RPSs, are given in [3] and [7]. Small-RPS concepts could employ individual units, stacked as needed, or could follow a modular RTG (Mod-RTG) design where the GPHS modules would be stacked and housed together. Both approaches could provide scalability to the power system, as required by the mission. These systems should be multi-mission capable and high g-load tolerant, in order to enable the largest number of missions. Concepts utilizing small, standard and advanced RPSs are discussed below.

Additional Power System Options

In this section a brief discussion is provides on chemical (i.e., batteries and fuel cells), solar and beamed power sources.

Batteries are energy storage devices, utilizing internal chemical power. These scalable energy storage systems are highly reliable, but heavy, presenting a significant impact on the total system mass. Voltage or current can be increased by connecting units in series or parallel. The life cycle of a battery is influenced by temperature; depth-of-discharge; rate of charge and discharge; and degree of overcharge. Primary batteries are not rechargeable and usually last for short durations, measured in hours. Therefore, they are typically used on launch and entry/re-entry vehicles, and on short-lived planetary entry probes. Batteries provide well-regulated power, typically 28±5 V. Examples for these in-

clude Lithium-Thionyl Chloride (Li-SOCl2) and Lithium-Carbon Monofluoride (LiCFx) cells. The specific energy (at 0°C) for Lithium based primary batteries today is ~250 Wh/kg, which is expected to grow to ~400 Wh/kg and ~600 Wh/kg in 5 and 10 years, respectively. (At lower temperatures the performance degrades – e.g., by 3 to 5 fold at -80°C.) Secondary batteries are rechargeable, and are only used for energy storage. Examples include Lithium-Ion, Lithium Polymer Electrolyte, Lithium Solid-State Inorganic Electrolyte and advanced Lithium-Sulfur (Li-S) batteries. Secondary batteries are important during peak load operating modes, where the power requirement exceeds the power output from the main power source (e.g., from an RPS), or during eclipses or overnight operations. However, their performance is lower than those for primary batteries. For example, the specific energy (at 0°C) for the present state of practice is ~100 Wh/kg, which is expected to increase to ~120 Wh/kg and ~200 Wh/kg in 5 and 10 years from now. The battery lifetime is also expected to increase from today's 5 years to 10 and 15 years, respectively.

Fuel cells can be used for human missions that require power in the multi-kilowatt range for up to ~10 days (e.g., on Space Shuttle flights, and were used on the Apollo Moon landings). They have higher specific energies than batteries.

Flywheels can be used as alternatives to secondary batteries. They are attractive for low-Earth orbiting missions, requiring reusable energy storage up to 5 kWh or more. Flywheels are not chemical power sources, but included here for completeness. Detailed discussions on primary and secondary batteries, fuel cells, capacitors and flywheels are given in [8].

Solar power generation utilizes the Sun as an external power source, and converts its energy into electricity. Solar flux decreases with the inverse square of distance from the Sun. For Mars surface missions, additional decrease can be contributed to the atmosphere and potential dust storms. Latitude, seasonal and diurnal changes also play a role in solar availability and intensity. The solar constant (S) at the orbital distance of Earth from the Sun is 1367 W/m^2. Compared to that (100%), solar irradiance values are significantly lower at Mars, as

measured in orbit (43%), on the surface under clear conditions (22%) and under cloudy conditions for local or global storms (13% to 6.5%) [7]. Solar radiation can be converted into electric power using solar thermal collectors or photovoltaic (PV) arrays (see Figure 1). Solar panel size and mass scales linearly with power. Photovoltaic arrays employ solar cells for power conversion. Some of these include single crystal Silicon cells and single junction Gallium Arsenide cells, converting photons of near infrared energy to usable energy. Multi-junction or multi-layer solar cells, such as Gallium Indium Phosphide/Gallium Arsenide, use different spectrums of sunlight, hence increasing the conversion efficiency. Typical conversion efficiencies for these three types are: ∼14.8-16.6% for Si; ∼19-22% for GaAs; and ∼22-26.8% for GaInP/GaAs [9]. These solar panels degrade at a rate of ∼3.75%; 2.75% and 0.5%, respectively [10]. Important characteristics of solar cells include: high efficiency; good radiation, UV and atomic oxygen tolerance; long life; robustness for mechanical stress tolerance; high reliability and low cost. Similarly, the arrays can be characterized by their specific power; stowed volume; cost; and reliability. The main solar array categories include body mounted; rigid; and flexible or deployable configurations. Others include concentrator, electrostatically clean and high temperature arrays. The state of practice for body mounted array areal power is ∼350 W/m². For rigid arrays the specific power is 30-60 W/kg, with a corresponding specific volume of 5-10 kW/m³. For flexible or deployable arrays these are 40-80 W/kg and 10-15 kW/m³, respectively, but the arrays may require complex deployment. Further information on these technologies can be found in [9].

It should be noted that the technologies discussed above are not suitable at significantly higher power levels. For power levels over ∼5 kW(e) *nuclear fission reactors* could be considered. However, fission reactors are not discussed further in this paper.

Finally, *power beaming* is addressed for completeness. Power beaming by microwave or laser from space to Earth or between space assets was suggested as early as in 1968. Landis provided a numerical example for power beaming from Earth to the Moon. Assuming a GaAs laser diode array with a lens diameter of 2 m; a distance of 4×10^8 m; and a diffraction limited beam spread (accounting for atmospheric turbulence); he calculated the total spot radius at the Moon to be 250 m with a corresponding illuminated area of 0.2 km². Using a 12 MW(e) power source at the sending end (e.g., on Earth), the received power at the Moon would be ∼50 kW(e), after all conversion and beaming losses are accounted for. This corresponds to an end-to-end beaming efficiency of ∼0.4% [11]. Furthermore, collector arrays with the size of ∼40 football fields would present severe logistical problems for landing, deployment and maintenance. Microwave and laser beaming technologies differ in many ways, including antenna configurations. However, beaming efficiencies and antenna size are similar between the two, hence the same conclusions would apply. Calculations indicated that at these low power conversion efficiency levels, power beaming from stationary Mars orbit to the surface is less advantageous than power generation on the surface. Therefore, it is concluded that power-beaming technologies require significant improvements (i.e., 2 orders of magnitude in conversion efficiency from ∼0.4% to ∼40%), before they can be seriously considered.

POTENTIAL NEXT-DECADE ROBOTIC MARS MISSIONS

The pathway for Mars exploration can be discussed from science or engineering points of view. The first could address the line of science enquiries and themes, while the second could describe the sequence of missions over a given time period. Pathways should also maintain analysis and instrument capabilities to allow for cross cutting paths for better program flexibility and response to discoveries. Mission concepts that can populate these various pathways reflect the recommendations of the National Academies [12] from a scientific point of view, while programmatic considerations are based on NASA's priorities and budget allocation. At present, NASA is performing an institution-wide planning activity to establish these pathways for all targets of interest, while reflecting the Vision for space exploration. Therefore, at this point only

a generic list of potential missions can be assembled, without the relating pathways. These possible missions are summarized in Table 2, including some of the already launched or selected missions (e.g., MRO, Phoenix, MSL).

The listed missions are categorized as Scout, Moderate, Large and Flagship. These classes correspond to assigned real-year dollar mission costs of ~$500M, ~$750M, ~$1B and multi-$B, respectively. Based on an assumed decadal budget allocation for the Mars Exploration Program, it has been calculated that for the 2010-2020 time period the program could support:

1. ~5 Large missions; or

2. ~10 Scout class missions; or

3. A mixture of Large, Moderate and Small missions.

Flagship class large human precursor and human missions will not likely start until after the second decade. Therefore, it is beyond the scope of this assessment and not discussed further.

The costs include mission development, focused technology assessments, launch vehicle cost, and mission operations.

For this decade, Mars missions under development include the Phoenix Scout mission and the Mars Science Laboratory (MSL) rover. These new missions would add to the existing assets currently operating at – or on the way to – Mars, namely the Mars Reconnaissance Orbiter (MRO), Mars Global Surveyor (MGS), Mars Odyssey, and the Mars Exploration rovers (Spirit & Opportunity).

Potential next decade missions (between 2011 and 2020) could include a scout mission in 2011, and a number of landed missions, such as Mars Sample Return, Mars Network Lander with multiple (~4-10) small landers, and an Astrobiology Field Laboratory rover using MSL heritage. Orbiters will likely add to this set, which may include a resurrected Mars Science / Telecom Orbiter (note that the original MTO mission was recently canceled). Over the past years additional concepts were also considered, including a deep drill for subsurface access to ~50-100 m, and sub-MER class fetch rovers. Second decade

(between 2021 and 2030) technology demonstration missions could include In-situ Resource Utilization (ISRU) landers and other large human precursor missions. To date, these second decade missions are in the early formulation phase, thus the final mission concepts will be significantly influenced by the direction of future Mars science exploration pathways.

IMPACT OF RPS OPTIONS ON MARS MISSION ARCHITECTURES

Preliminary Pre-Phase-A studies typically focus on designs, which optimize the science operations phase. However, some of the earlier mission phases could also impact the design. This is particularly relevant for RPS enabled missions, where the heat generated by these power systems must be mitigated during *Earth storage, launch, cruise* and *EDL* (entry, descent and landing) phases, in addition to the surface operation phase [13].

Storage, Launch, Cruise & EDL Phases

RPSs are fueled at a US Department of Energy (DoE) facility and must be integrated with the spacecraft on the launch pad prior to launch. (The storage phase can be as long as 2 years, which should be accounted for during power system degradation calculations.) RPS integration with the spacecraft is overseen by the DoE. It requires a spacecraft design with easy accessibility, which could introduce an ever-increasing challenge as the number of RPSs increase for human precursor and human missions. The ambient temperatures and heat transfer mechanisms also vary throughout the mission phases. On Earth, during the storage and launch phases, the temperatures and pressures are terrestrial, where the mechanisms include convection, conduction and radiation. During the cruise phase in space (vacuum), radiation is the dominant heat transfer mode, while conduction through the RPS housing and along the cooling fins also plays a role. EDL on Mars utilizes an aeroshell for atmospheric entry. Thus, during cruise the RPS is encapsulated inside an aeroshell. The RPS-generated heat must be removed through

Selected & Potential Missions	Class	Power System Option(s)
Orbiters (e.g., **MRO**[1])	Moderate/Large	Solar (typical for Mars orbiters)
Phoenix[1]	Scout	Solar selected
Mars Science Laboratory (MSL)[1]	Large	RPS (MMRTG[2])
Scouts (small missions)	Scout	Solar (cost cap may limit RPS usage)
Multi-Lander Network	Moderate/Large	Small-RPS or Solar
Astrobiology Field Lab (AFL) rover	Large	RPS (based on MSL heritage)
Mars Sample Return (MSR)	Flagship	Solar (or RPS)[3]
MSR Fetch rover (sub-MER class)	Scout-Large	Small-RPS or Solar[3]
Deep Drill	Large	RPS (or Solar)[3]
ISRU Testbed, Tech demo	Large	Solar (or RPS)[3]
Large human precursor & manned	Flagship	TBD (architecture dependent)

Table 2: Approved and Candidate Mars Exploration Missions for the next decade and beyond, with estimated mission class and power system options. ([1] Approved missions; [2] MMRTG is baselined; [3] based on preliminary power trades.)

a secondary cooling system. A typical configuration would use a fluid loop and external radiators. This adds mass to the spacecraft and complexity to the mission.

In comparison, integration of other types of power systems with the spacecraft, such as solar panels and batteries, do not represent integration challenges and thus will not be discussed further.

In-Orbit & Surface Operation Phases

At 1.5 AU Mars is relatively close to the Sun, thus solar availability could point to the use of solar panels. However, solar power may not be suitable for all of the missions listed in Table 2. On the surface, seasonal changes at the polar regions could result in insufficient illumination that would shut down the mission for up to 6 months [7], and potentially could fail the spacecraft. Therefore, the power source selection strategies should be discussed on a location-by-location basis and in regards to mission objectives and duration.

Orbiter missions around Mars have historically used solar power generation, combined with secondary batteries to mitigate eclipses and other non-nominal operating conditions. It is likely that future Mars orbiters will continue to use solar panels.

On the surface, longer missions to partially or permanently shadowed areas must address thermal survival mitigation. The thermal environment could be maintained by resistance heating or through utilization of the waste heat from RPSs or RHUs. In the first case, applicable to solar powered applications, resistance heating would require secondary batteries, which would be charged from the solar panels during the Martian day. While this approach could work near the equatorial region, or for short missions at hight latitudes during polar summers, it would not be suitable for long duration polar missions. During polar winters – without the Sun – the battery charge would not be sufficient to maintain survival temperature for months at a time. For the second case, where RPSs are used, the excess heat from the radioisotope source could be directly used to keep components warm. Conduction plates, fluid loops or heatpipes are typical ways for RPS heat utilization.

Over the next decade – extended until 2020 in this discussion – potential missions could include a subset of Scout class missions, moderate or large orbiters, a Mars Sample Return (MSR) mission, a multi-lander network, multiple rover concepts – such as an Astrobiology Field Laboratory (AFL) rover, a sub-MSL class rover, and a sub-MER class rover –, and a Deep Drill. ISRU demonstration and other human precursor mission might follow after 2020.

Orbiters will likely use heritage from previous

Mars orbiter missions. A *Scout or near-Scout class orbiter* could include a Synthetic Aperture Radar (SAR), a magnetometer, a gravitometer, trace gas detection, and aeronomy related instruments. A moderate orbiter could use either a surface payload providing 15 cm/pixel resolution from an assumed 150 km orbit, or an atmospheric payload. A large orbiter might combine the surface and atmospheric payloads into a single orbiter mission. Science instruments on orbiters could detect trace gas elements or prospect for in-situ resources for future ISRU missions. Potentially, the orbit of these spacecraft could be raised to provide a high-orbit telecom relay.

The *Mars Sample Return* mission was recommended by NRC in the SSE Decadal Survey [12]. Two *MSR* mission configurations were considered, both with a skycrane (MSL heritage) and an Earth Return Vehicle (ERV). The first option is based on the Science Steering Group (SSG) defined mobility version, using a Mach-3 parachute and one to two landers. The second assumed a "groundbreaking" configuration with prior sample caching and active rover delivery to the lander. Both configurations employ a Mars Ascent Vehicle (MAV) to bring the sample to Mars robit for rendezvous with the ERV. The MSR mission has been primarily designed with solar panels, however, alternative trade options have been also assessed with RPSs. One of the high power requirements on this mission are due to keeping the propellant on the MAV above a certain temperature. The elongated shape of the fuel tank necessitates a significant heat input, supplied by the power system. During daytime this power can be provided by the solar panels, while during night time resistance heating is powered by secondary batteries. This operating scenario could benefit from RPSs, utilizing both the generated power and the excess heat to keep the fuel tank warm.

The *Multi-Lander Network* mission was also recommended in [12]. In mission studies three versions of 4-element networks were assessed with increasing complexity. Each element would act as a seismology / meteorology station, utilizing existing orbiters for telecom, or would use their own relay satellite. The landers would be powered by single GPHS module based small-RPSs,

generating about 12-20 W(e) (based on conversion efficiency). High power modes would include the continuous operation of the seismometer and periodic telecom. The small-RPS configuration would be specific to this lander, because the power system would be embedded inside the structure and would have to survive the high g-loads (up to 2000g) during landing on a crushable material enabled aeroshell [13]. If required, the number of lenders could be expanded up to 10 elements.

Mobility concepts could include rovers at various sizes and mission classes. The largest, the *Astrobiology Field Laboratory* rover, might be constrained to maximize MSL heritage, including the skycrane, about 80 kg of science instruments, and an MMRTG as the power source. (RPS enabled spacecraft typically use a hybrid power system, where during peak power modes power is drawn from the RPS and the batteries, while during low power modes the batteries are recharged [6].) Potentially, the rover could utilize the updated MMRTG. The additional power could increase traversing capability, and high volume data collection and transfer (e.g, high definition streaming video from the surface). Detailed discussions on rover concepts, enabled by RPSs are provided in [5] Smaller rover concepts are based on *Mars Exploration Rover heritage*. The simplest version, which in the study is referred to as MER-A, includes airbag landing and the same instrumentation as MER, with the addition of a Raman spectrometer [14]. Then, this configuration was slightly scaled up to allow for a new 30 kg payload, Viking type powered landing and solar panels. This version is called MER-C. Alternative power system options included small-RPSs. Both MER rovers, flown in 2003, used 1.3 m^2 solar panels, generating about ~1000 Wh/sol at BOL, which is predicted to drop to ~600 Wh/s at the end of life (EOL). The same amount of power could be generated with two single GPHS module based small-RPSs. The MER-C rover would use about twice as much power, which could be generated with 4 small-RPSs [5]. The smallest *sub-MER* class rovers are referred to as *fetch rovers*. These have also been assessed with two small-RPSs, and have been considered to support the MSR mission, or to perform inde-

pendent prospecting for future ISRU missions. Therefore, if small-RPSs were available, then the Mars program could reassess the power system options for these missions. Large scale prospecting on the surface would likely necessitate larger RPS enabled rovers, long mission durations, and significant traversing capabilities. These rovers should cover 10s of square kilometers to map the extent of the resources. Traversing capabilities at this scale would need MSL class rover configurations or possibly more. (MSL is currently designed with a single MMRTG.)

The *Deep Drill* concept has been considered with a pinpoint landing configuration, MSL landing heritage, and a subsurface access to ~50 m. Mission trade studies extended the depth to ~100 m. The mission architecture assumed either solar or RPS based power generation. With an optimized design, drilling to 50 m could be supported with 4 small-RPSs, generating about half the power of a standard MMRTG. For the 100 m excess more power would be needed, which could be provided by an MMRTG. An upgraded MMRTG (see Table 1) could enhance this mission. The high power modes would include the drilling operation; telecommunications, either Direct-to-Earth or through a relay orbiter; and science analysis with a Gas Chromatograph / Mass Spectrometer (GC/MS).

ISRU testbeds have been briefly considered with power requirements around 1 to 2 kW(e) using solar panels. Ultimately, RPSs could be employed potentially up to 5 MW(e). As discussed earlier, this would assume Cassini-Huygens mission level Pu^{238} requirements, but with dynamic power conversion. Note that ~27 kg of Pu^{238} would generate 13.5 kW(t) thermal power, which must be rejected through the cruise phase. The required radiator size would be ~7 times larger than the one designed for the MSL rover's external radiators during cruise phase. This would have a mass impact on the mission. In addition, during EDL this excess heat would probably be removed through phase change materials (PCM), further increasing the overall system mass. Solar panels and a near equatorial landing location could solve this problem. However, if the mission is required to access the Martian poles then a hybrid system with solar palels, RPSs and secondary batteries could be used.

During polar summers the RPSs could supplement solar power generation. During polar winters the operation could be scaled back and the power and heat generated with the RPSs could keep the system above survival temperatures. Detailed analysis on ISRU type surface missions with these configurations will be completed at a future time.

Flagship class human precursor and human missions, which might appear in the century's third decade or later, would require significantly higher power levels than the above missions. Therefore, these are not discussed in this paper.

CONCLUSIONS

NASA's Mars Exploration Program is currently in a re-planning phase. Therefore, the various missions discussed in this paper provide only an overview of the possible missions expected over the next decades, without prioritization. The main focus was placed on Radioisotope Power System options, strategies and availabilities, in connection with these potential missions.

It is likely that the program will employ both solar and radioisotope based power generation in order to address the four exploration goals and to enable upcoming Mars exploration pathways. Historically, for orbiting spacecraft solar power generation has been found to be the best suited option, due to simplicity; low mass; high reliability; and high power availability. This technology could be also used for some of the surface applications.

RPSs would be ideally suited on the surface for non-equatorial, multi-seasonal missions, where large and flagship class missions could be configured with single or multiple RPS units. However, smaller – potentially single GPHS module based – small-RPSs could enable a set of missions, configured with either single or stacked multiple units, responding to various power level requirements.

From now until the end of the next decade 3 to 4 missions could employ single MMRTG or upgraded MMRTG units.

Specifically, for the rest of this decade, until 2010, three new missions are in progress or under development. These are the recently launched

MRO (2005); the Scout Phoenix lander planned for launch in 2007; and the MSL rover scheduled for 2009. MSL could use an MMRTG, while the other missions will be powered by solar panels.

In the following decade, from 2011 to 2020, RPS enabled missions could include the AFL rover, possibly powered by an MMRTG or an upgraded MMRTG; and the multi-lander network, potentially powered by a high g-load tolerant custom small-RPS or solar panels. At a lower likelihood, the pathway could include a Deep Drill (to ~50-100 m), possibly powered by an MMRTG or an upgraded MMRTG. Also, a small MER class rover or a sub-MER class fetch rover could be powered by solar panels or by small-RPSs.

Note that all of the MMRTG or upgraded MM-RTG enabled missions were designed with a single power source. For the assessed configurations an MMRTG is more mass efficient than two SRGs. (Missions using SRGs are required to carry a redundant unit. The redundancy requirement increases power system mass and complexity, although the total plutonium requirement would be still half of that of a single MMRTG.)

Small-RPS units could generate power in the 12 to 20 W(e) range. If this power system becomes available, an additional 2 to 3 missions could be enabled by single GPHS module based small-RPSs, utilizing up to a sum of 5 to 12 units. Small-RPS enabled missions could include 4 to 10 lander elements of the multi-lander network; a Deep Drill (to ~50 m) with 4 GPHS modules; small rovers with 2 to 4 modules; and potentially other scout class missions not yet determined. These power systems could be also considered for adjunct elements on larger missions. Small-RPSs would reduce plutonium requirement and mission cost when compared to MMRTGs; while extending mission capabilities and mission duration when compared to solar panels.

It should be noted that if all of the discussed potential Mars missions – considered over the next 15 years – would be approved, the RPS powered missions would likely require less than 75% of the plutonium used on the latest flagship class Solar System Exploration mission (that is the Cassini-Huygens mission).

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